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ON CAPTURE EFFECT OF FM DEMODULATORS

by

Park Soon Sang

March 1989

Thesis Advisor: Glen A. Myers

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On Capture Effect of FM Demodulators

by

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ABSTRACT

The reception of FM carriers is characterized by a capture effect whereby the message of the dominant carrier is recovered when two or more FM carriers are present. This research uses a computer to form a type of average of the instantaneous frequency of the receiver input. The results establish that averaging (smoothing or lowpass filtering) of the instantaneous frequency reveals the capture effect. The effect on capture of bandwidth and amplitude ratio for the case of two carriers is revealed. The results show that capture can occur when two carriers are separated by as little as 0.17 dB in amplitude.

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I. INTRODUCTION

Radio communication usage continues to expand because the military and commercial markets seek (1) personalized service such as paging and cellular applications, (2) ever greater exchanges of text and data (facsimile, computer networking), and (3) transfer of high quality signals (television). The messages are "traffic". The carriers are sine waves.

There are two primary ways of carrying messages using sinusoids. The message can cause to vary (modulate) the amplitude or the argument (angle) of the sinusoid. These are called amplitude modulation (AM) and angle modulation (∠M) respectively.

Amplitude modulation can assume various forms such as double sideband with carrier, double sideband suppressed carrier and single sideband. Angle modulation can be either frequency modulation (FM) or phase modulation (PM). With analog messages, there is little difference between FM and PM. In fact, FM hardware would be used should PM be chosen. Consequently, PM with analog messages is, in practice, reduced to FM. [Ref. 1: pp. 198–199]

Frequency modulation exhibits several interesting characteristics not shared by AM. Two such characteristics are threshold effect and capture effect. The threshold effect relates to the quality (signal–to–noise ratio) of the demodulator output as a function of the quality of the received signal (demodulator input). Below "threshold" quality of the input, the output quality deteriorates rapidly. The capture effect relates to the ability of the demodulator to recover the message of the dominant carrier when two or more FM carriers are present.

This research is concerned with the capture effect of FM. Computer simulation is used to verify an idea concerning the reason for (origin of) the capture effect of FM demodulators.

Background information on FM and the capture effect is presented in chapter II of this thesis. Chapter III describes the computer simulation procedure and program. Results of the simulation are contained in Chapter IV. Conclusions and recommendations are listed in chapter V. The computer program is listed in the Appendix. A list of references is provided.

II. BACKGROUND

A. EQUATION FOR FM CARRIER

An angle modulated sinusoid is expressed as

$$s(t) = B\cos[\phi_i(t)] \tag{2.1}$$

where the constant B is the carrier peak amplitude. A complete oscillation cycle occurs whenever the argument $\phi_i(t)$ changes by 2π radians. The instantaneous frequency of the angle modulated wave $s(t)$ is defined by

$$f_i(t) \triangleq \frac{1}{2\pi}\frac{d\phi_i(t)}{dt} \tag{2.2}$$

Frequency modulation is that form of angle modulation for which the instantaneous frequency $f_i(t)$ varies in accordance with the baseband signal or message voltage $m(t)$. Typically, a linear relationship is chosen so that

$$f_i(t) = f_c + k_f m(t) \tag{2.3}$$

where f_c is the frequency of the unmodulated carrier and the constant k_f represents the frequency sensitivity (in Hertz per volt) of the modulator. From Eqs. (2.2) and (2.3), the angle $\phi_i(t)$ is

$$\phi_i(t) = 2\pi f_c t + 2\pi k_f \int_0^t m(\tau)\,d\tau \tag{2.4}$$

where, for convenience, the angle of the unmodulated carrier wave is assumed to be 0 at $t = 0$. The frequency modulated wave is, therefore,

$$s(t) = B\cos[2\pi f_c t + 2\pi k_f \int_0^t m(\tau)\,d\tau] \tag{2.5}$$

B. CAPTURE EFFECT

Consider the case of two FM carriers, $s_1(t)$ and $s_2(t)$, present at the demodulator input and in the same frequency band. It is well known in practice that the output of the demodulator is the message of the dominant carrier. That is, if

$$s_1(t) = B_1 \cos[2\pi f_c t + 2\pi k_f \int_0^t m_1(\tau) d\tau]$$

$$s_2(t) = B_2 \cos[2\pi (f_c + \epsilon) t + 2\pi k_f \int_0^t m_2(\tau) d\tau] \qquad (2.6)$$

then the output of the demodulator is proportional to

$$m_1(t), \text{ when } B_1 > B_2$$

$$m_2(t), \text{ when } B_1 < B_2$$

The carrier frequency offset ϵ is any value such that both $s_1(t)$ and $s_2(t)$ are in the same operating frequency band of the receiver/demodulator. This inherent ability of an FM demodulator to suppress weaker FM carriers is called capture effect.

The FM demodulator can be a phase locked loop, a slope detector which includes Foster–Seeley and ratio detectors, or a pulse counting discriminator.

C. ANALYSIS

As shown by Eq. (2.3), the instantaneous frequency $f_i(t)$ of a frequency modulated carrier is proportional to the message $m(t)$ being carried. Consequently, it is claimed in the literature that the output voltage of a frequency demodulator is proportional to $f_i(t) - f_c = \Delta f_i(t)$ [Ref. 2: pp. 169–172]. This is indeed the case in practice when the demodulator input is a single frequency modulated carrier. However, it is not the case, because of the capture effect, when the demodulator

input is multiple frequency modulated carriers.

The instantaneous frequency of the sum of two frequency modulated carriers can be derived as follows. Let

$$v(t) = B_1 \cos\phi_1(t) + B_2 \cos\phi_2(t) \tag{2.7}$$

Using trigonometric identities, Eq. (2.7) can be written as

$$v(t) = C \cos\phi_3(t) \tag{2.8}$$

where,

$$C^2(t) = B_1^2 + B_2^2 + 2B_1B_2\cos[\phi_1(t) - \phi_2(t)] \tag{2.9}$$

$$\tan\phi_3(t) = \frac{B_1\sin\phi_1(t) + B_2\sin\phi_2(t)}{B_1\cos\phi_1(t) + B_2\cos\phi_2(t)} \tag{2.10}$$

From Eq. (2.2), the instantaneous frequency $f_i(t)$ is

$$\begin{aligned} f_i(t) &= \frac{1}{2\pi}\left[\frac{d}{dt}\phi_3(t)\right] \\ &= \frac{1}{2\pi}\frac{d}{dt}\tan^{-1}\left[\frac{B_1\sin\phi_1(t)+B_2\sin\phi_2(t)}{B_1\cos\phi_1(t)+B_2\cos\phi_2(t)}\right] \\ &= \frac{(B_1\phi_1'\cos\phi_1+B_2\phi_2'\cos\phi_2)\,C+(B_1\phi_1'\sin\phi_1+B_2\phi_2'\sin\phi_2)D}{2\pi(C^2+D^2)} \\ &= \frac{B_1^2\phi_1'+B_2^2\phi_2'+[B_1B_2\cos(\phi_1-\phi_2)](\phi_1'-\phi_2')}{2\pi[B_1^2+B_2^2+2B_1B_2\cos(\phi_1-\phi_2)]} \end{aligned} \tag{2.11}$$

where,

$$C = B_1 \cos\phi_1(t) + B_2 \cos\phi_2(t)$$

$$D = B_1 \sin\phi_2(t) + B_2 \sin\phi_2(t)$$

and ϕ_1', ϕ_2' represent $\frac{d}{dt}\phi_1(t)$ and $\frac{d}{dt}\phi_2(t)$ respectively.

As before, for an FM carrier

$$\phi_i(t) = 2\pi f_c t + 2\pi k_f \int_0^t m_i(\tau)\, d\tau$$

$$\phi_i'(t) = 2\pi f_c + 2\pi k_f m_i(t) \qquad i = 1, 2 \tag{2.12}$$

where the carrier frequencies for both messages are assumed to be the same and

$m_i(t) = i$ th message

k_f = frequency sensitivity of the frequency modulator in Hertz/volt

Equations (2.8) through (2.12) can be reduced and interpreted for particular messages. For example, let the two messages be tones where

$$m_i(t) = D_i \cos 2\pi f_i(t) \qquad i = 1, 2 \tag{2.13}$$

For simplicity, let $D_1 = D_2 = 1$. Then,

$$\begin{aligned}\phi_i(t) &= 2\pi f_c t + 2\pi k_f \int_0^t \cos(2\pi f_i \tau)\, d\tau \\ &= 2\pi f_c t + \frac{k_f}{f_i} \sin 2\pi f_i t\end{aligned}$$

$$\phi'_i(t) = 2\pi f_c + 2\pi k_f \cos 2\pi f_i t \qquad i = 1, 2 \tag{2.14}$$

Using these values in Eq.(2.11) gives

$$f_i(t) = \frac{f_c(B_1{}^2 + B_2{}^2) + k_f \cdot X + B_1 B_2 Y \cdot Z}{B_1{}^2 + B_2{}^2 + 2B_1 B_2 Z} \tag{2.15}$$

where

$$X = B_1^2 \cos 2\pi f_1 t + B_2^2 \cos 2\pi f_2 t$$

$$Y = 2f_c + k_f(\cos 2\pi f_1 t + \cos 2\pi f_2 t)$$

$$Z = \cos[2\pi k_f(\frac{1}{2\pi f_2} \sin 2\pi f_2 t + \frac{1}{2\pi f_1} \sin 2\pi f_1 t)]$$

Equation (2.15) is plotted in Figs. 2.1.a through 2.2.c along with $m_1(t)$ and $m_2(t)$ where $f_1 = 1$ Hz and $f_2 = 1.3$ Hz. It can be seen that there are many impulselike frequency deviations from the message waveforms. The variable in Fig. 2.1 is β (modulation index for FM). The bandwidth of the modulated carrier is related to β. In general, bandwith increases linearly with β [Ref. 3: pp. 194–197].

There are two major factors that affect the graph of instantaneous frequency. First, the bandwidth of the modulated carrier affects the spacing in time between adjacent impulse–like frequency deviations. Figures 2.1.a through 2.1.c show that as the bandwidth decreases, the spacing increases. Second, the difference in magnitude of the two modulated carriers affects the extent of the deviation. Figures 2.2.a through 2.2.c show that as the magnitude difference increases, the deviation extent decreases.

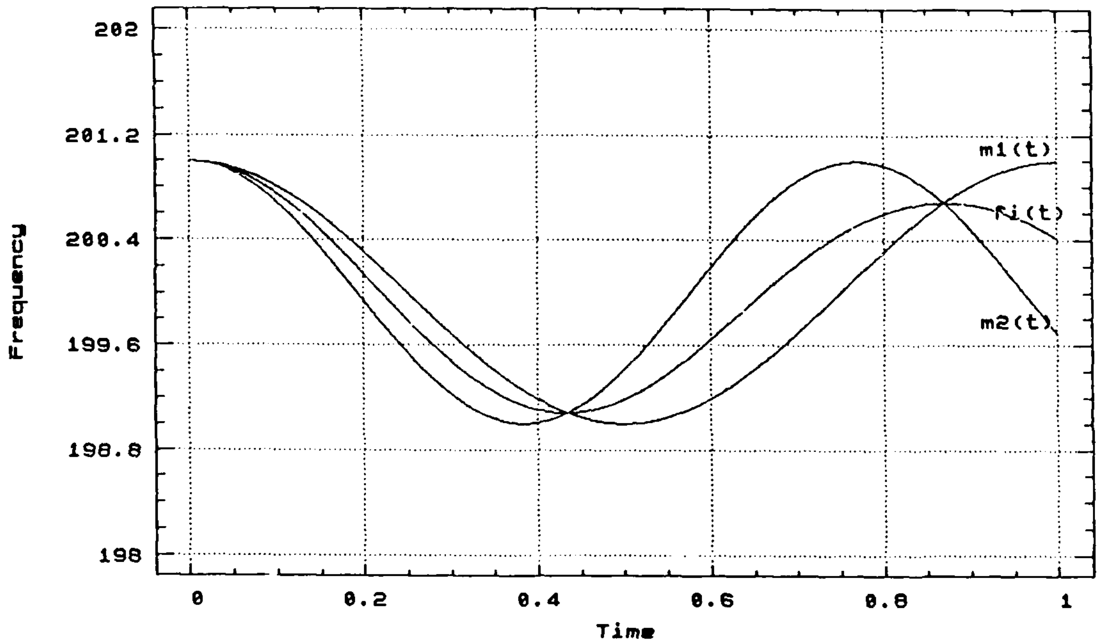
However, these results do not show specific evidence of capture. Rather, they suggest that the instantaneous frequency needs to be averaged over a short time interval to reveal the capture effect. The same thing is true for the case of close (but different) carrier frequencies, as shown in Chapter III.

The idea that the capture effect is caused by the lowpass filtering operation of frequency demodulation led to this research. Since lowpass filtering can be thought of as averaging (or smoothing), it was decided to investigate the capture effect by averaging the instantaneous frequency using a computer.

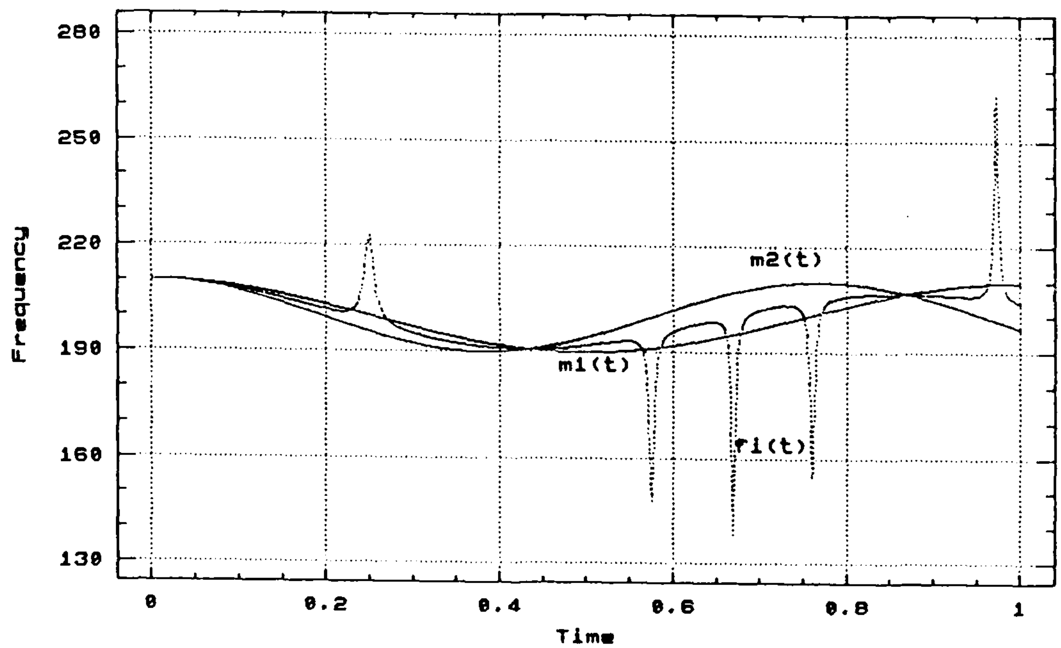
So, in hardware, the averaging is done by the lowpass filter (LPF). A LPF is part of every frequency demodulator (frequency–to–voltage or voltage–to–frequency converter). Consequently, the output of a frequency demodulator is a lowpass filtered version of instantaneous frequency deviation $\Delta f_i(t)$.

Again, lowpass filtering can be considered as a smoothing operation on the applied voltage. In this research, we used computer simulation to investigate the effect of smoothing of $\Delta f_i(t)$ to reveal the presence of capture. Smoothing is created by averaging time intervals between adjacent zero crossings of the FM carrier. Since this interval (T_1) represents the time required for π radians excursion of the argument of the cosine carrier, and since π radians is taken as a half cycle, then two such intervals ($T_1 + T_2$) become a full cycle and $\frac{1}{T_1+T_2}$ is the number of cycles per second or the instantaneous frequency for $T_1 + T_2$ seconds. Averaging N such groupings provides a smoothed value of or short–term average of the instantaneous frequency over that expanded time interval.

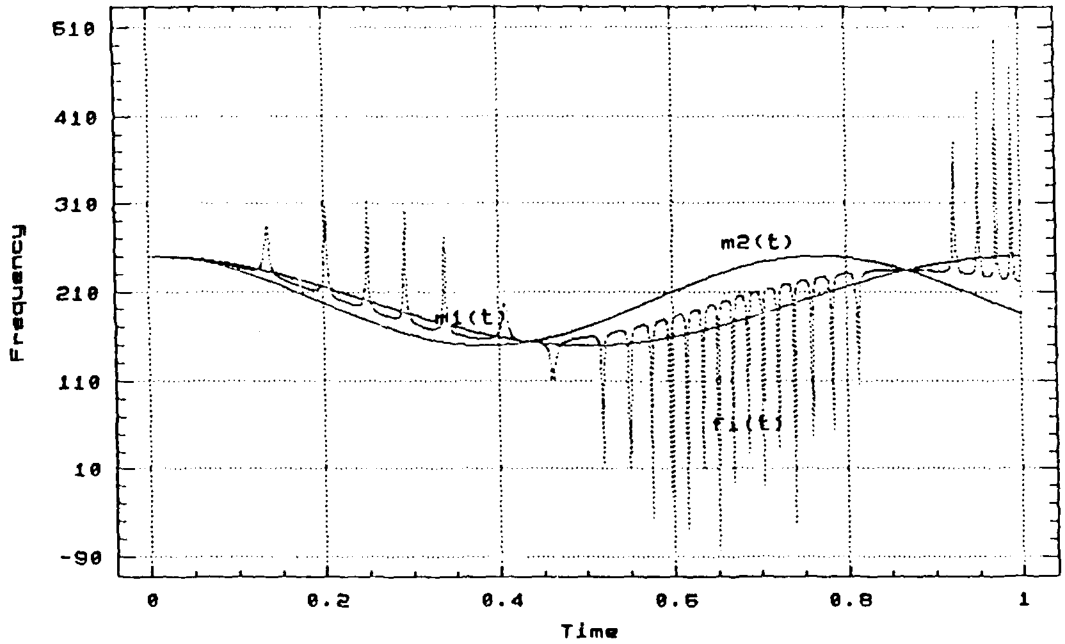
A computer program was used to approximate T_1 and T_2 for every interval between zeros of $v(t)$. These values are then averaged and the results are plotted. The program is explained in Chapter III.



a. $\beta = 1$



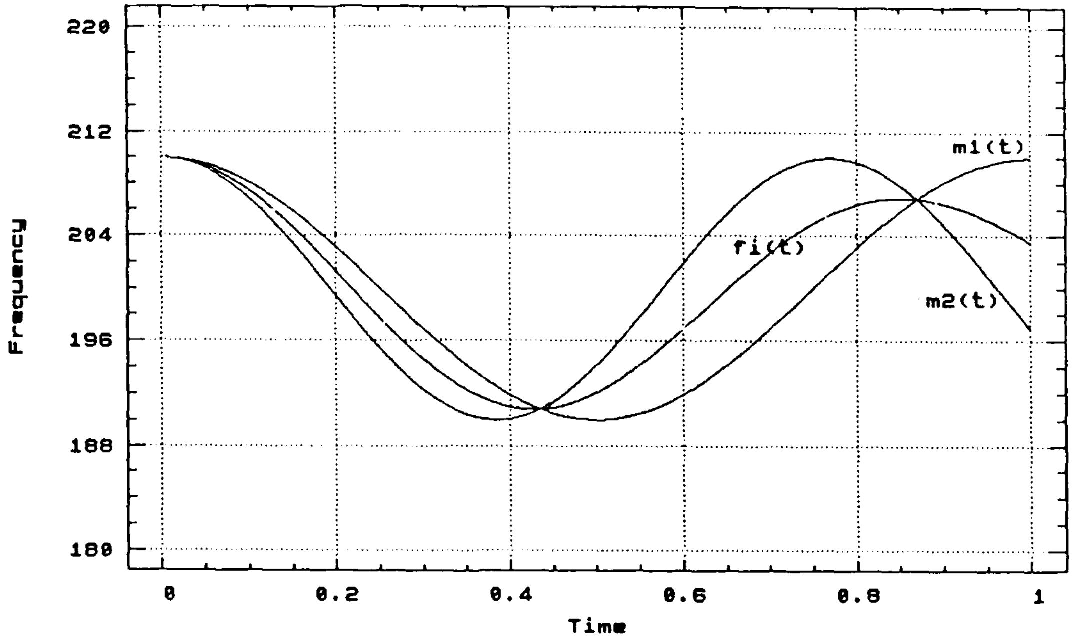
b. $\beta = 10$



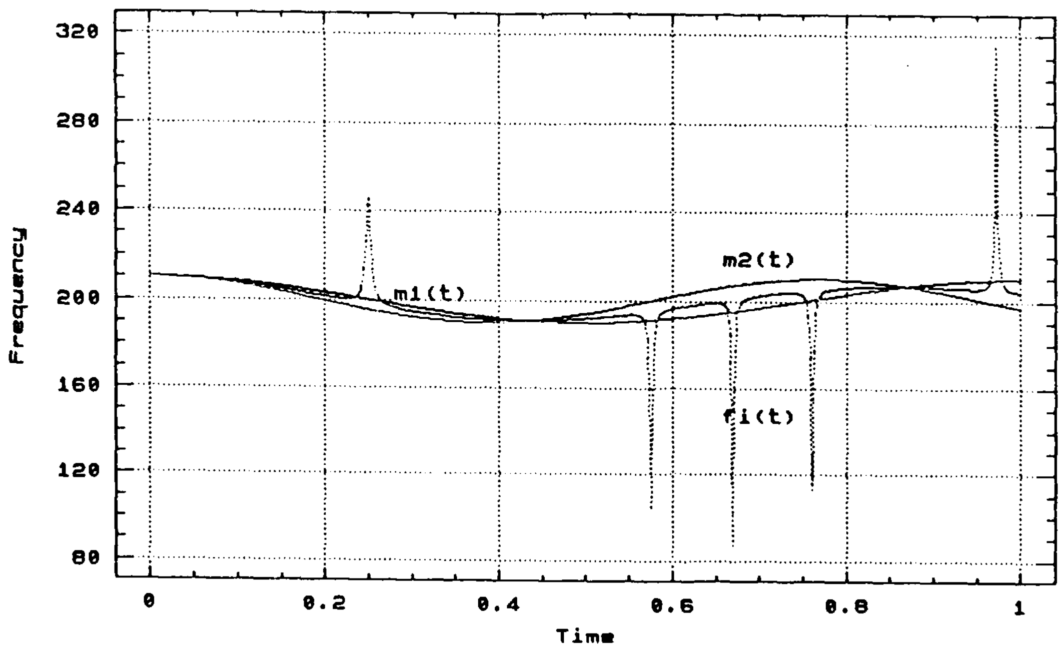
c. $\beta = 50$

Fig. 2.1 Instantaneous Frequency for Tone Messages

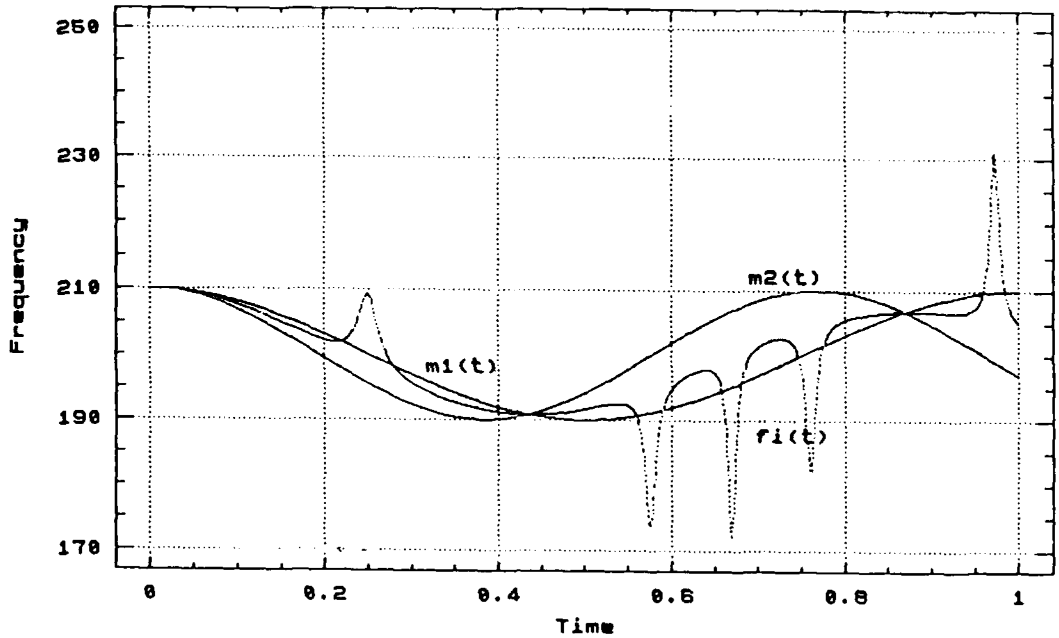
where $a_1/a_2 = 1.2$, $f_c = 200$ Hz, $f_1 = 1$ Hz, $f_2 = 1.3$ Hz



a. $a_1/a_2 = 1$



b. $a_1/a_2 = 1.1$



c. $a_1/a_2 = 1.5$

Fig. 2.2 Instantaneous Frequency for Tone Messages

where $\beta = 10$, $f_c = 200$ Hz, $f_1 = 1$ Hz, $f_2 = 1.3$ Hz

III. SIMULATION PROCEDURE

The FM demodulator, including LPF, is simulated by a computer program so that critical parameters, such as signal amplitudes, bandwidth of the FM system, message forms, and interval of averaging, can be easily changed. Since the sampled version of the demodulator input forms a sequence of numbers, it is convenient to consider it as a row (or column) vector. Once that is done, the rest is simple manipulation of the row (or column) vector.

A. WAVEFORM GENERATION

The desired waveform $v(t)$ can be generated using a simple routine (WAVEGEN). In this routine, the carrier amplitudes, values of k_f, carrier frequencies and message frequencies are input parameters which can be changed. This resulting wave is sampled at a rate which will provide the desired accuracy in measuring the time between adjacent zeros of $v(t)$. In this work, a carrier frequency of 200 Hz and sampling rate of 12 kHz are used.

The sampled values contain no information about frequency. Rather, the number of samples between zero crossings are related to frequency because the number of samples between zero crossings itself represents a half cycle oscillation of argument of $v(t)$ and its reciprocal can be interpreted as twice the frequency of that period. Therefore, the routine notes the polarity of each sample so that the number of samples between zero crossings (polarity changes) can be easily counted. This result is then used as the input for the next routine.

B. COUNTING

The number of samples between zero crossings (polarity changes) multiplied by the fixed sampling interval (λ) is considered to be taken as half the instantaneous period of that interval. So, a sequence of integers which consists of the number of samples between zero crossings need only be generated. The i th entry for this sequence is denoted by T_i, $i = 1, 2, 3, \cdots$ as shown in Fig. 3.1. The totality of entries forms a sequence of integers.

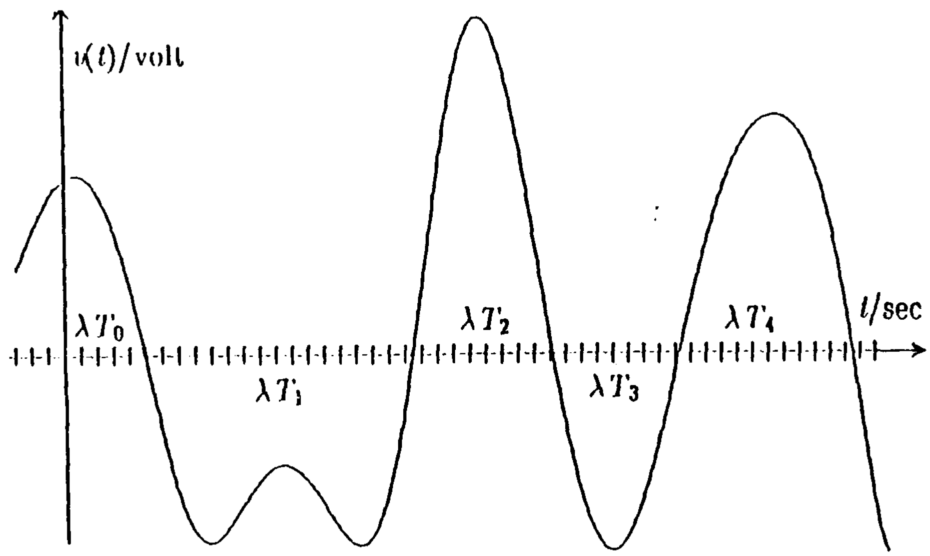


Fig. 3.1 Formation of sequence

Furthermore, T_i itself is a time index. Since there are $i-1$ entries before the current interval T_i, T_i is the period for the time $\sum_{k=1}^{i-1} T_k + \frac{1}{2}T_i$. (The middle of the interval T_i is selected for the time index of interval T_i. For example, the time index of T_3 is $T_1 + T_2 + \frac{1}{2}T_3$.)

Since the first and last interval may contain a number of samples that does not correspond to a complete interval between adjacent zeros, these two entries are not used in the averaging routine.

C. AVERAGING

Given the sequence of integers, any average $\bar{T}_k$ over N intervals is formed as

$$\bar{T}_k = \frac{\sum_{k}^{k+N} T_i}{N} \qquad k = \text{any positive integer} \tag{3.1}$$

$T_i = i$ th interval

$N =$ number of intervals averaged

Since frequency is taken as the reciprocal of the period, the averaged frequency, denoted by $\bar{f}_k$, is given by

$$\bar{f}_k = \frac{1}{2\bar{T}_k\ \lambda} \tag{3.2}$$

To obtain more realistic (smoother) results, a moving average is used rather than fixed time interval averaging. To illustrate this, assume a sequence of intervals as follows

$$T_1 \quad T_2 \quad T_3 \quad T_4 \quad T_5 \cdot \cdot \cdot \cdot \cdot$$

Then, if the average is done over 3 intervals, the averaged version of the sequence will have the following entries

$$\bar{T}_1 = \frac{T_1 + T_2 + T_3}{3}$$

$$\bar{T}_2 = \frac{T_2 + T_3 + T_4}{3}$$

$$\cdot$$

$$\cdot$$

$$\bar{T}_k = \frac{T_k + T_{k+1} + T_{k+2}}{3} \tag{3.3}$$

Again from the relationship between period and frequency (Eq.(3.2)), averaged version of frequency will form the sequence

$$\frac{1}{2\bar{T}\lambda}\ \frac{1}{2\bar{T}_2\lambda}\cdots\ \frac{1}{2\bar{T}_k\lambda}\cdots$$

In this case, the time indices for the averaged version of intervals are

$$\frac{T_1+T_2+T_3}{2} = \text{time index for } \bar{T}_1$$

$$T_1+\frac{T_2+T_3+T_4}{2} = \text{time index for } \bar{T}_2$$

$$T_1+T_2+\frac{T_3+T_4+T_5}{2} = \text{time index for } \bar{T}_3\text{, and so on.}$$

Generally, time indices for the moving average over N intervals are found as

$$\sum_{k=1}^{i-1} T_k + \frac{1}{2}\sum_{k=i}^{i+N-1} T_k \quad (\text{time index for } \bar{T}_i) \tag{3.4}$$

Since the values of each T_i are not the same, the averaged frequency values when plotted will not be equally spaced.

IV. SIMULATION RESULTS

With an average of 2 intervals ($N = 2$), the resulting plot is very similar to that of the analytical one. That is, when almost no averaging is done, the resulting plot should yield that of the analytical one. This is another way of verifying that the simulation program is running properly. As the number N of average intervals increases, the impulse–like frequency deviation becomes smaller and the overall frequency deviation approaches that of the stronger signal.

Figures 4.1.a through 4.5.c are the simulation results. The results are presented as averaged instantaneous frequency versus time. In all cases, the message $m_1(t)$ corresponds to that of the dominant carrier. The following variables are used to see the effect of system parameters.

a_1/a_2 = ratio of carrier amplitudes (1 through 1.5)

β = modulation index (1 for narrowband, 10 for wideband, 50 for very wideband FM)

f_1 = message 1 frequency (1 Hz for sinusoidal message)

f_2 = message 2 frequency (1.3 Hz for sinusoidal message)

f_c = carrier frequency (180 Hz through 200 Hz)

N = number of intervals averaged (2, 20, 40, 60, 80)

Various messages were used in the simulation. Figures 4.1.a through 4.1.c show the results when the messages are linear intrapulse FM (up CHIRP and down CHIRP). Figures 4.2.a and 4.2.b are for exponentially decaying and growing sinusoidal messages. Sinusoidal messages are used extensively to show the results for various correlations of the listed variables.

Even though there may be other factors which influence the capture effect, only the following four factors are investigated in this research.

A. EFFECT OF N (AVERAGING TIME)

Figures 4.3.a through 4.3.d shows the effect of N. The other factors (a_1/a_2, β, f_1, f_2, f_c) remain fixed. This factor is essentially the cause of the capture effect. As N increases, the instantaneous frequency increasingly resembles the message of the stronger signal.

B. EFFECT OF SIGNAL AMPLITUDE RATIO

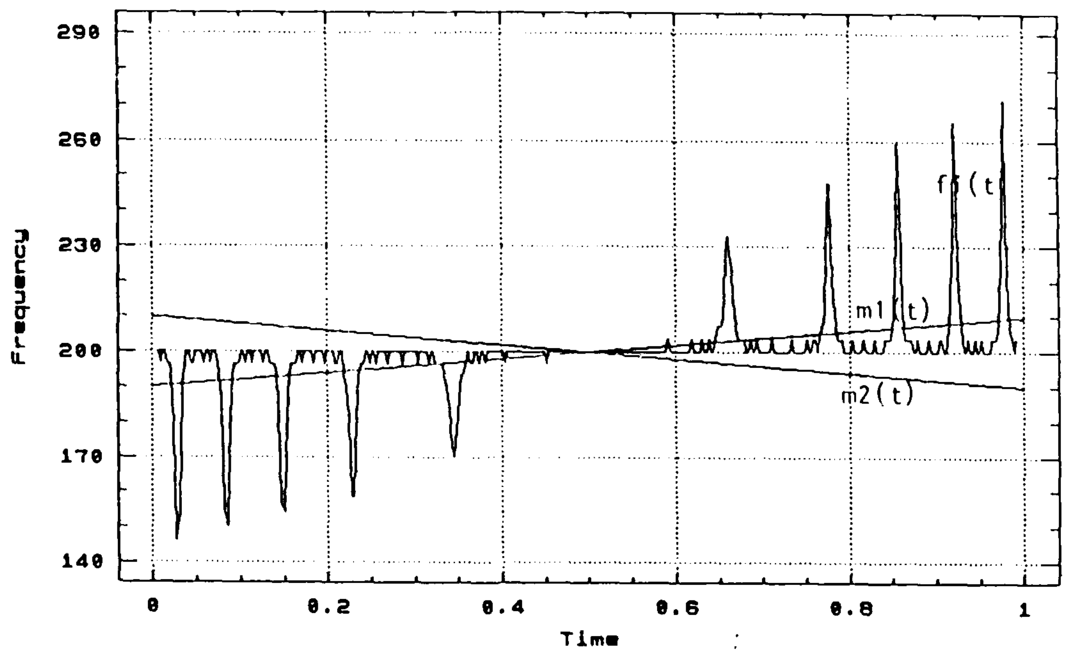
Figures 4.4.a through 4.4.d show the effect of signal amplitude difference. While the other factors remain fixed, a_1/a_2 varies from 1.01 to 2.0. The effect of signal amplitude difference is very interesting. Even with very small signal amplitude difference, the system still locks onto the stronger signal. For numerical comparison, the 0.8 dB difference case (Fig. 4.4.b) and 1.6 dB case (Fig. 4.4.c) show little difference. In the case of very small amplitude difference, more averaging is needed to see the capture effect. Figure 4.4.a indicates capture for a carrier separation of 0.17 dB ($a_1/a_2 = 1.02$).

C. EFFECT OF MODULATION INDEX

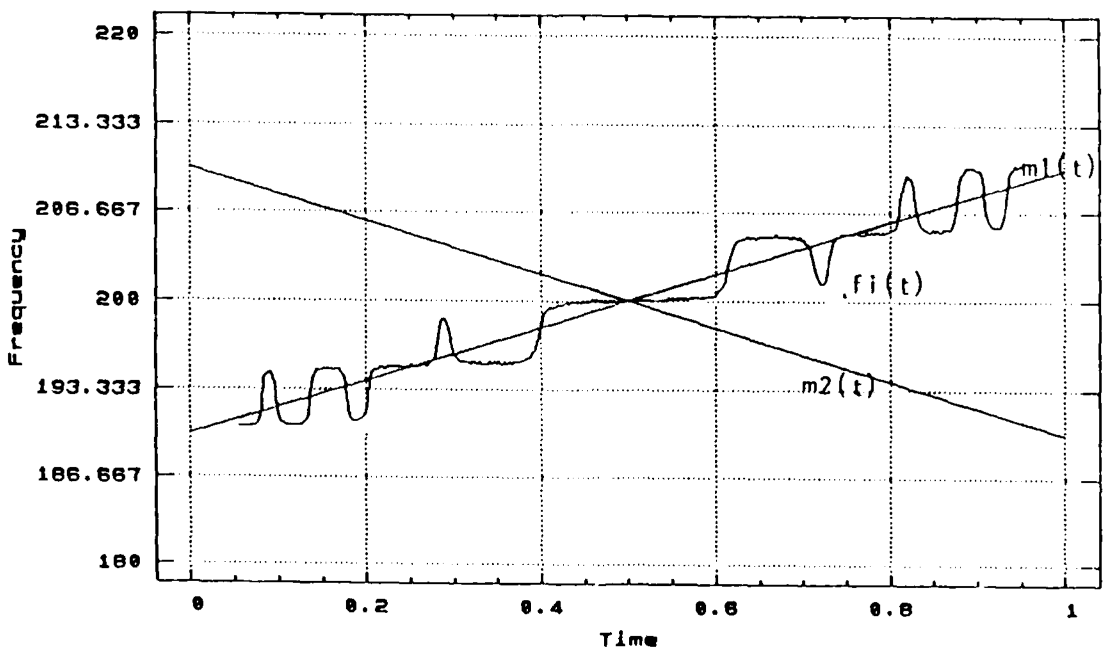
Modulation indicies are changed from 1 to 50 in Figs. 4.5.a through 4.5.c. Capture occurs for both narrowband FM and wideband FM. Since the narrower band FM shows fewer impulse–like frequency deviations, each of longer duration than those of wider band FM, narrow band FM needs to be averaged longer (see Fig. 2.1).

D. EFFECT OF CARRIER FREQUENCY DIFFERENCE

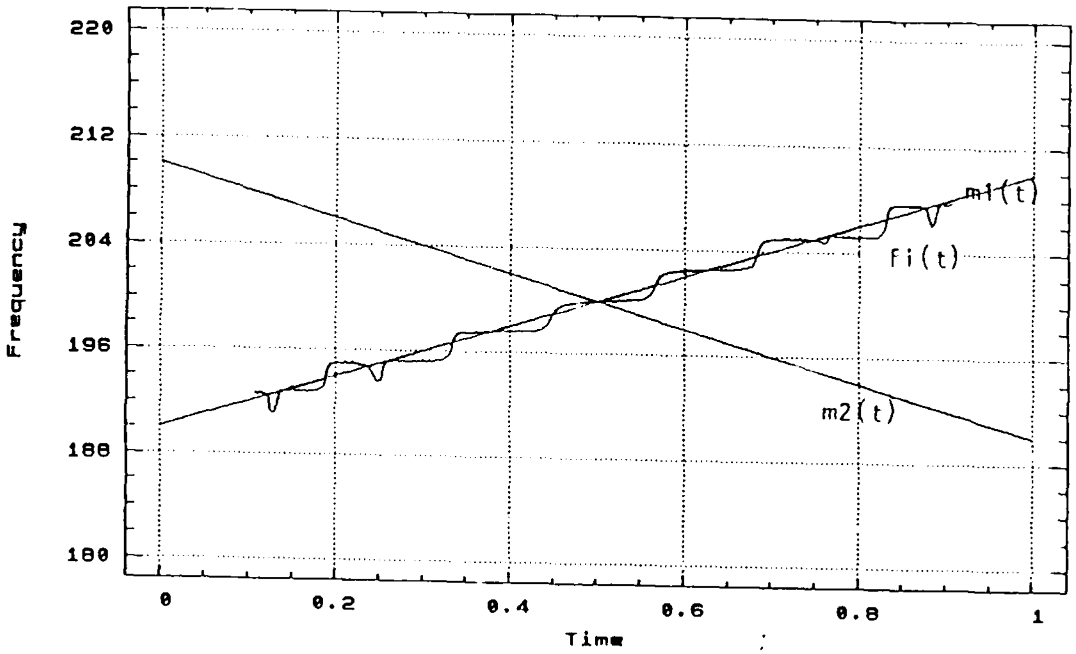
Figures 4.6.a and 4.6.b show the effect of carrier frequency difference on capture. It appears that capture becomes more complete as the carrier frequencies separate. Obviously, the two carriers must lie in the passband of the receiver (intermediate frequency amplifier) if they are to be present at the input to the demodulator.


290
260
230
200
170
140
Frequency
0
0.2
0.4
0.6
0.8
1
Time
fi(t)
m1(t)
m2(t)

a. $N = 2$

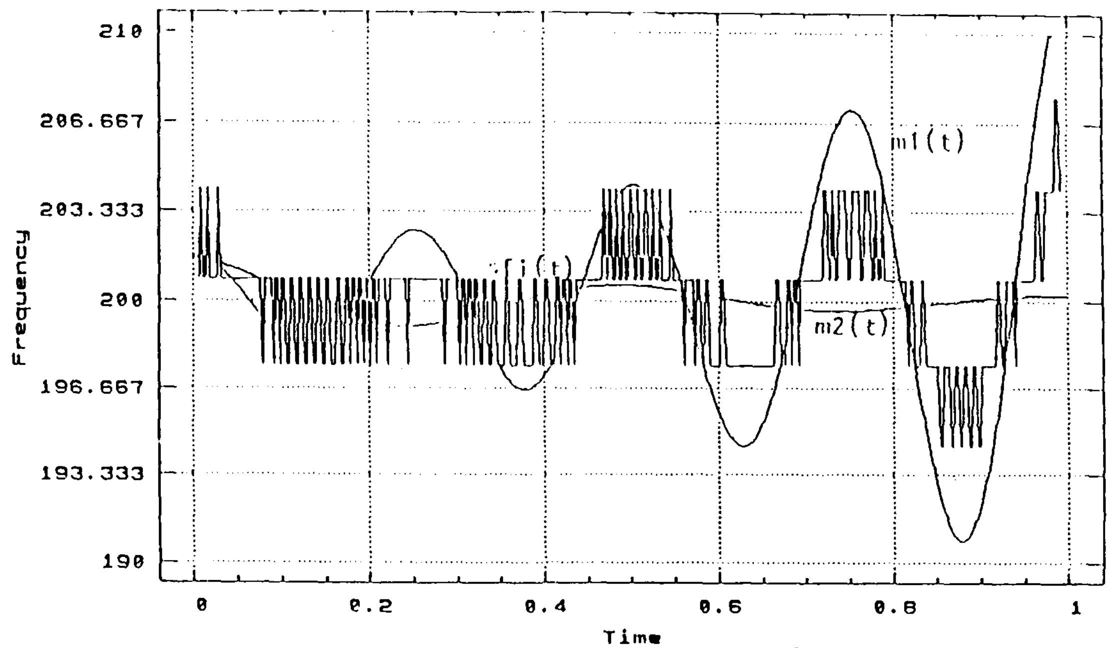

220
213.333
206.667
200
193.333
186.667
180
Frequency
0
0.2
0.4
0.6
0.8
1
Time
m1(t)
fi(t)
m2(t)

b. $N = 20$

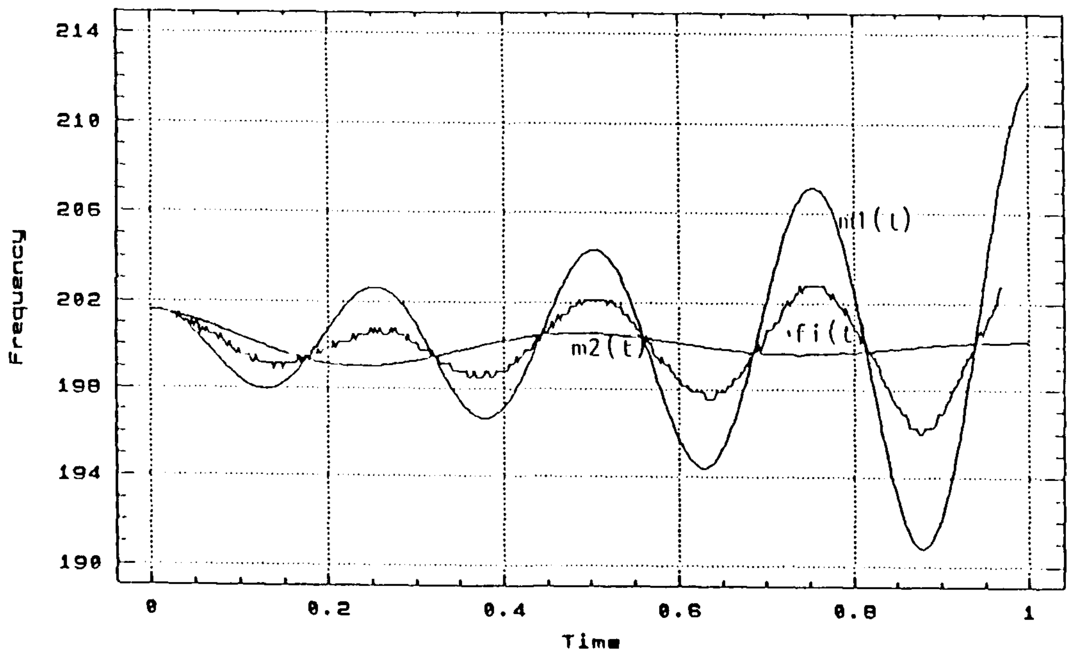


c. $N = 40$

Fig. 4.1 Average instantaneous Frequency Deviation for CHIRPS where $a_1/a_2 = 1.5$



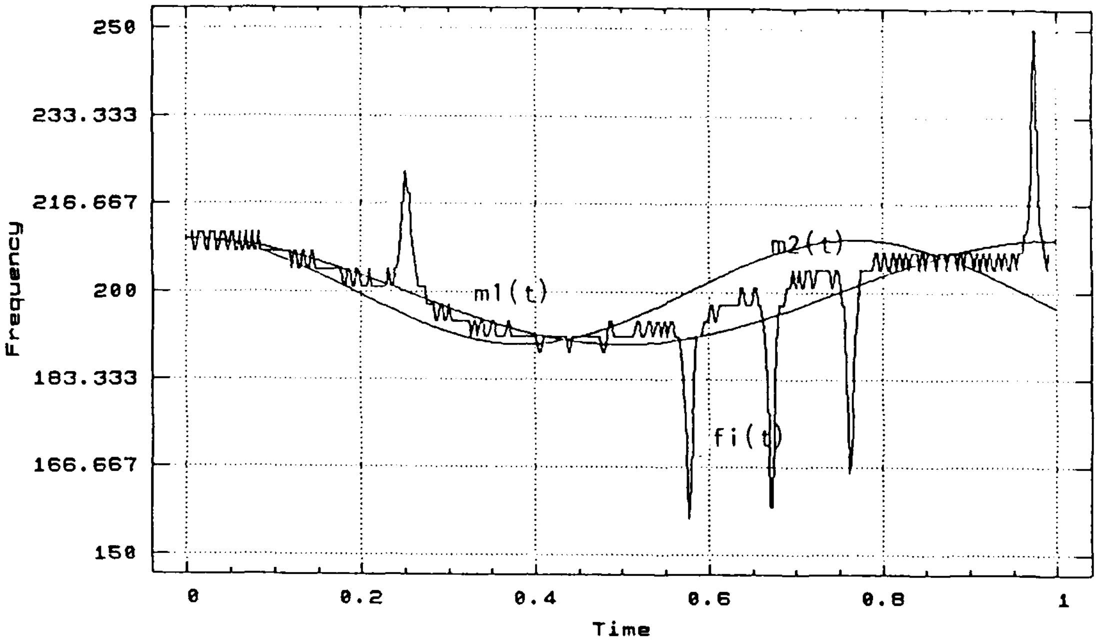
a. $N = 2$



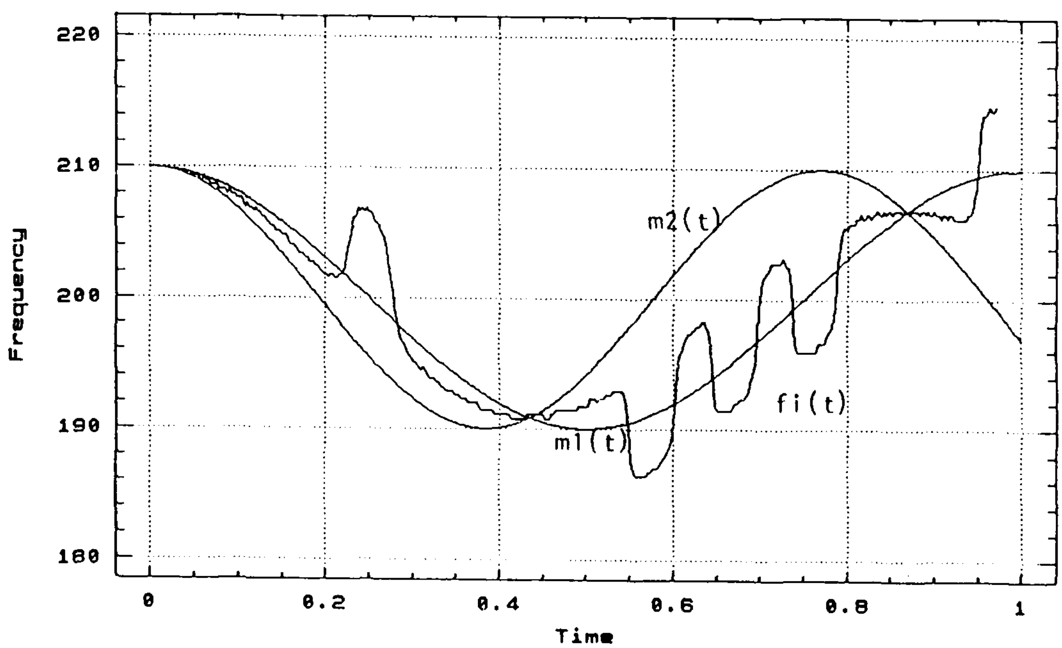
b. $N = 20$

Fig. 4.2 Average Instantaneous Frequency Deviation

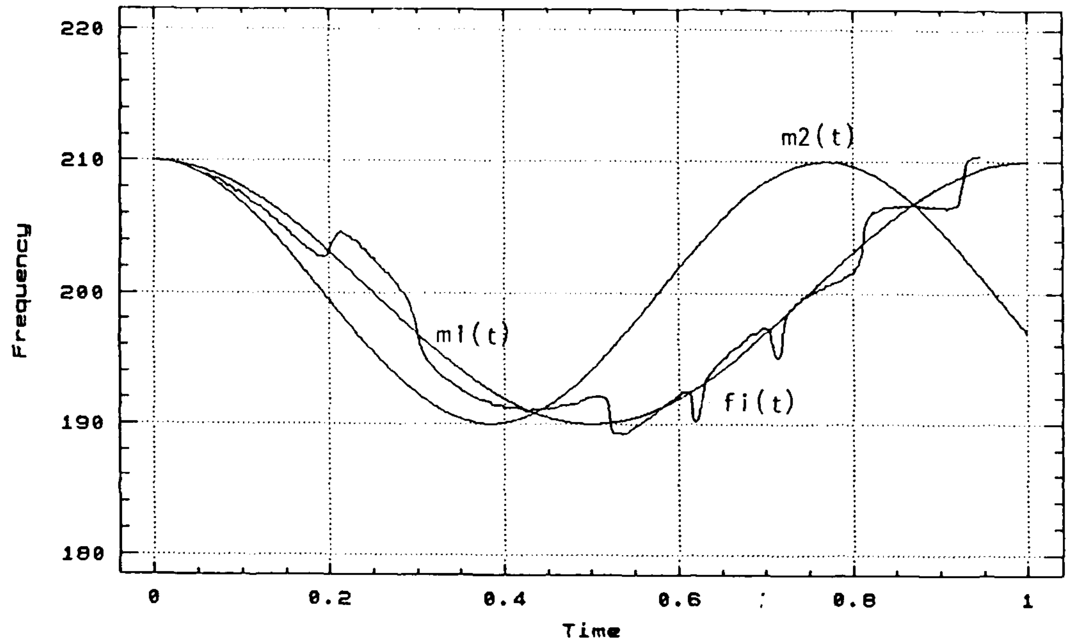
for Decaying and Growing Sinusoidal Messages where $a_1/a_2 = 1.2$


250
233.333
216.667
200
183.333
166.667
150
Frequency
0
0.2
0.4
0.6
0.8
1
Time
m1(t)
m2(t)
fi(t)

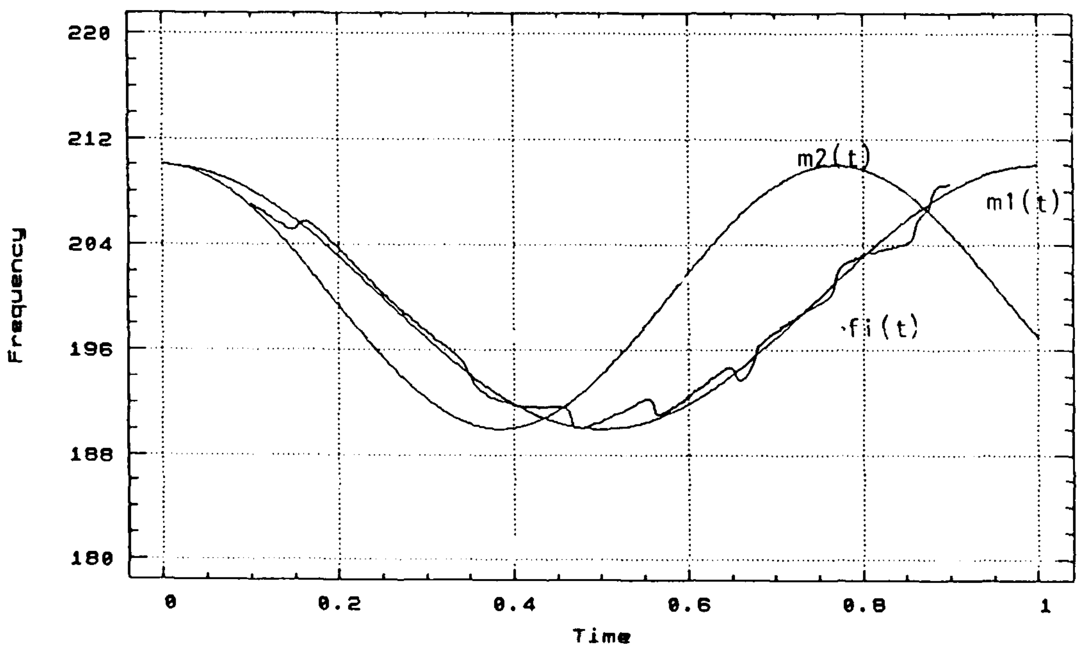
a. $N = 2$


220
210
200
190
180
Frequency
0
0.2
0.4
0.6
0.8
1
Time
m2(t)
fi(t)
m1(t)

b. $N = 20$

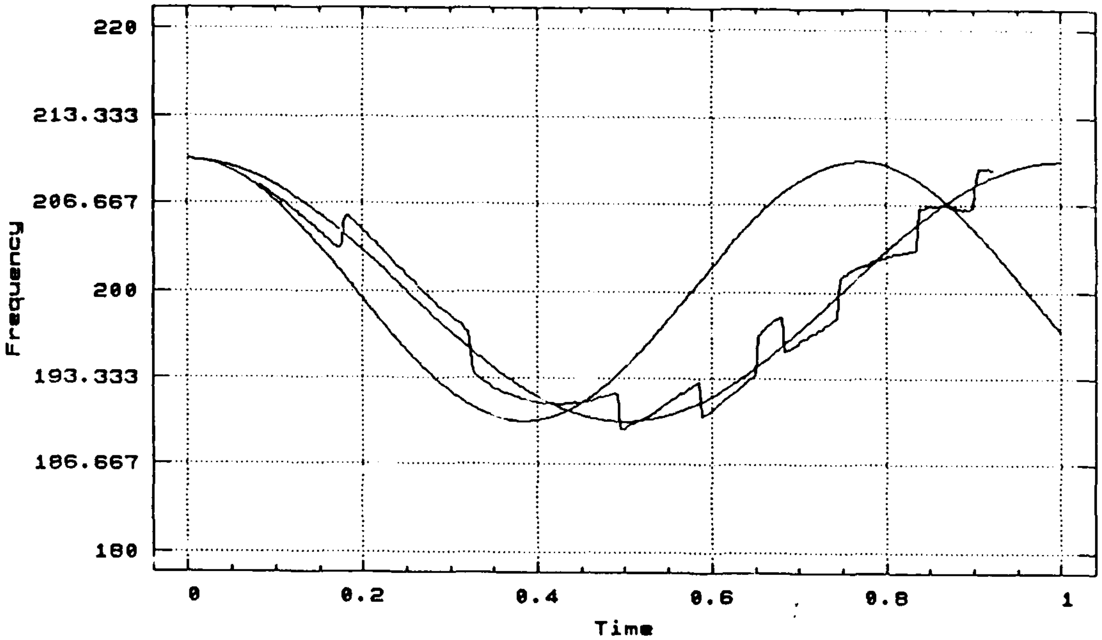


c. $N = 40$

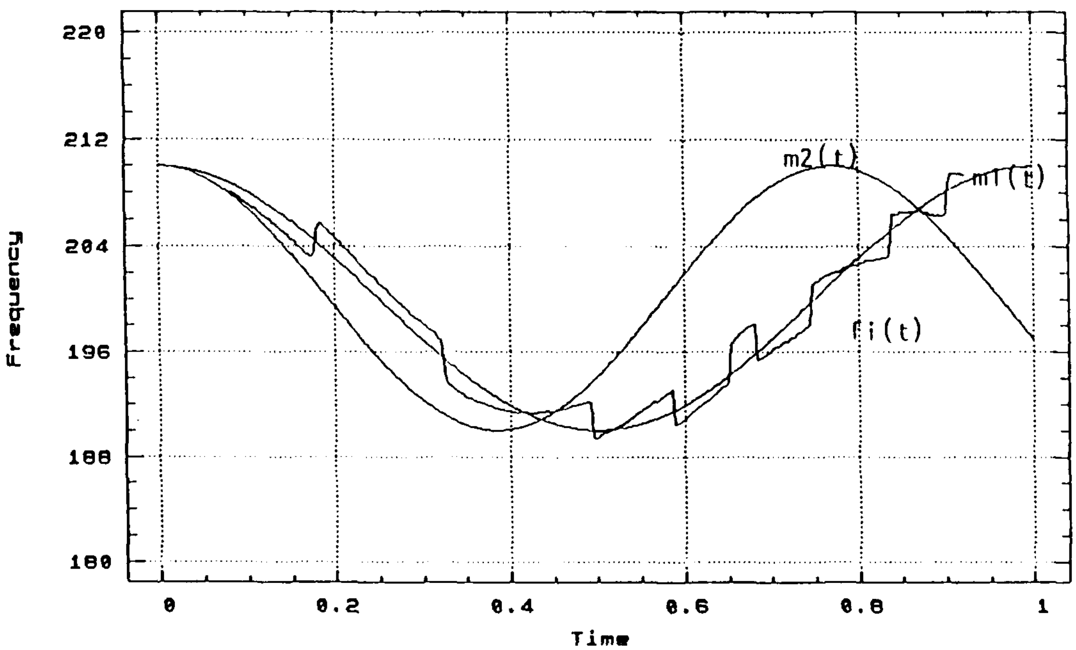


d. $N = 80$

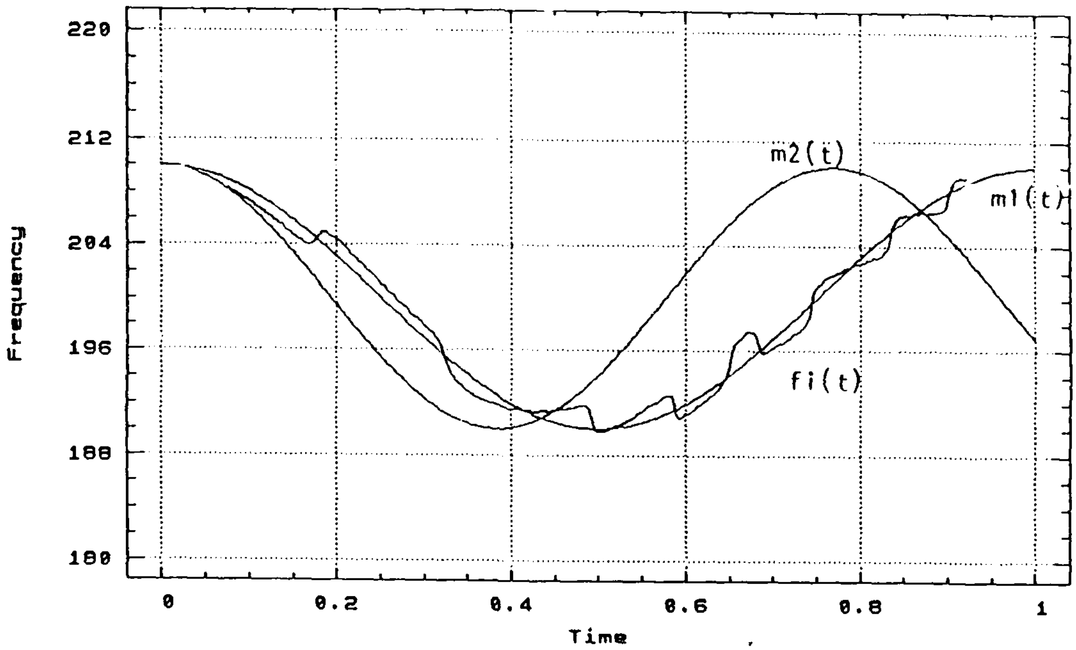
Fig. 4.3 Average Instantaneous Frequency Deviation for Tone Messages where $a_1/a_2 = 1.2$, $\beta = 10$, $f_c = 200$ Hz, $f_1 = 1$ Hz, $f_2 = 1.3$ Hz



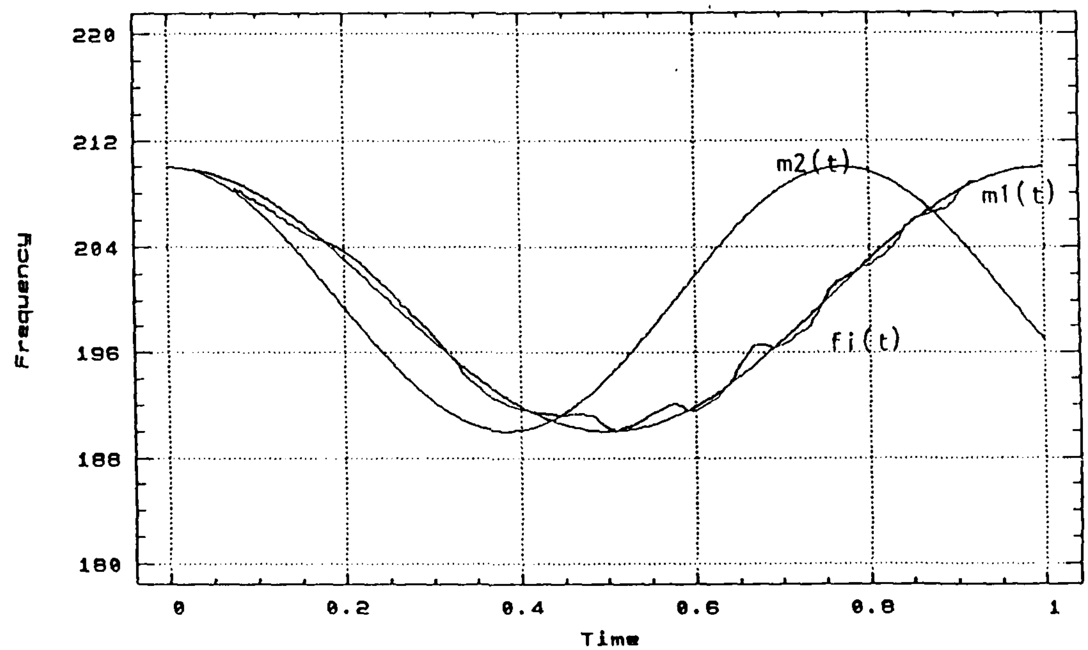
a. $a_1/a_2 = 1.02$



b. $a_1/a_2 = 1.2$

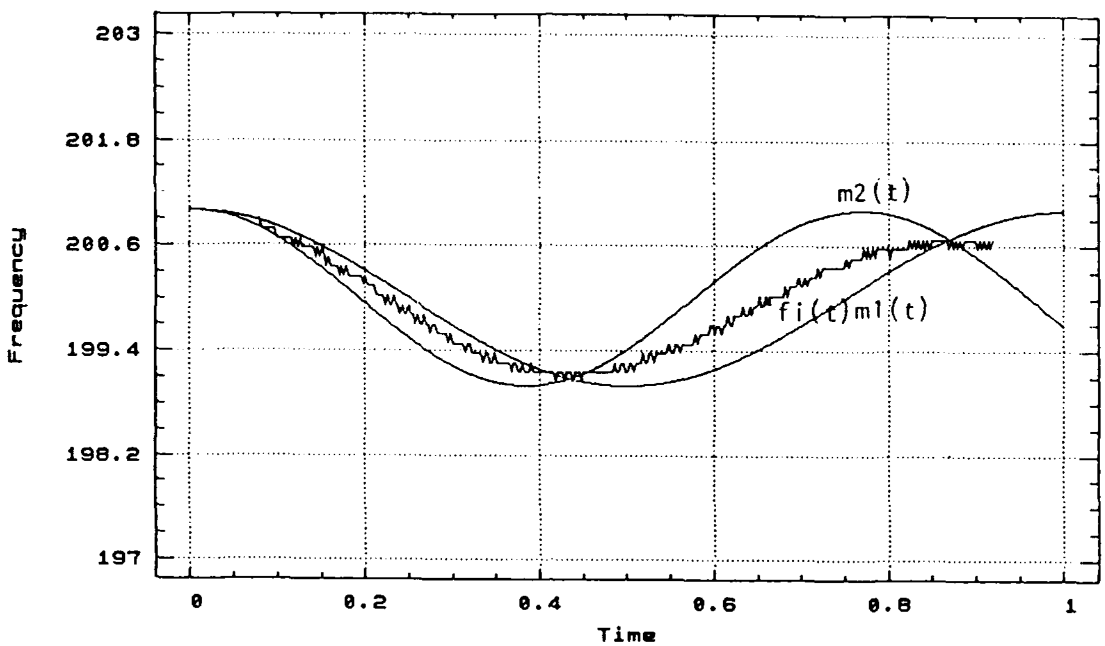


c. $a_1/a_2 = 1.5$

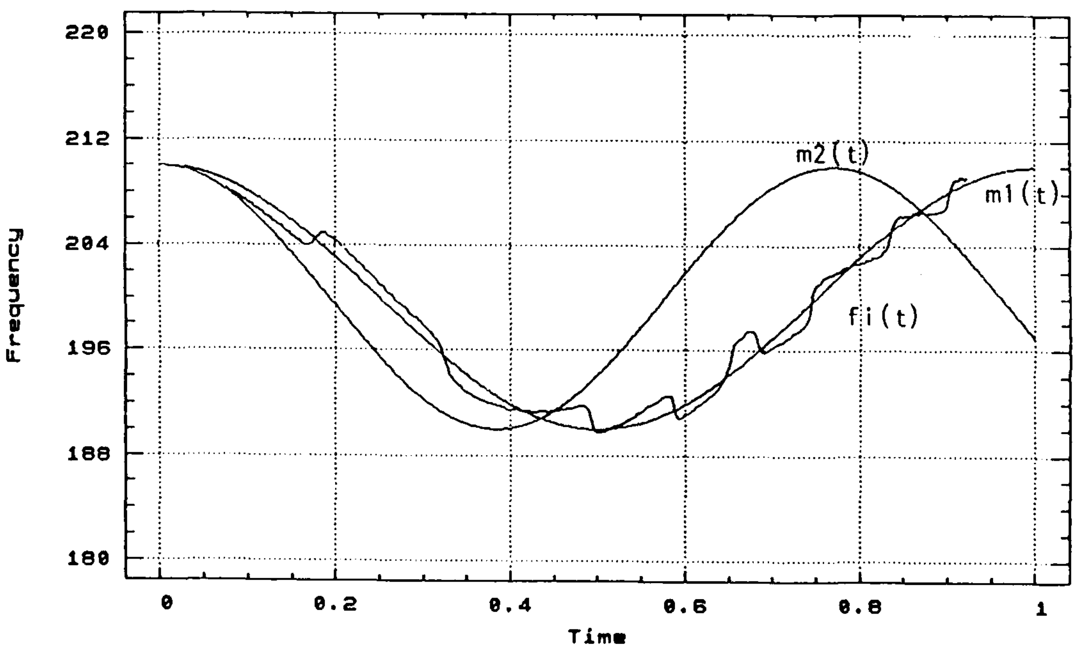


d. $a_1/a_2 = 2.0$

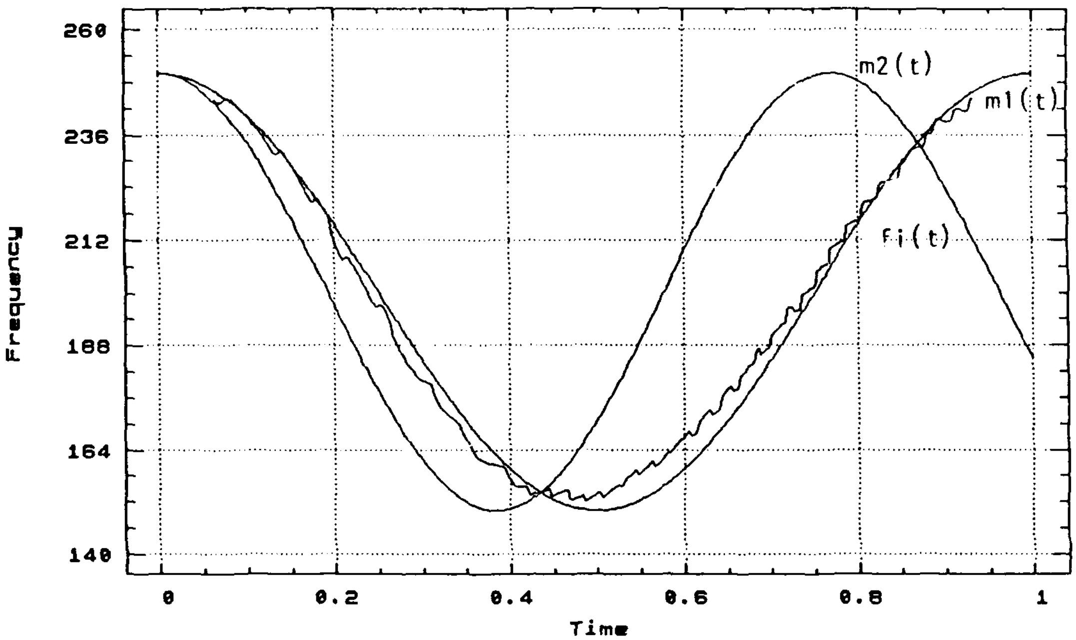
Fig. 4.4 Average Instantaneous Frequency Deviation for Tone Messages where $\beta = 10$, $f_c = 200$ Hz, $f_1 = 1$ Hz, $f_2 = 1.3$ Hz, $N = 60$



a. $\beta = 1$

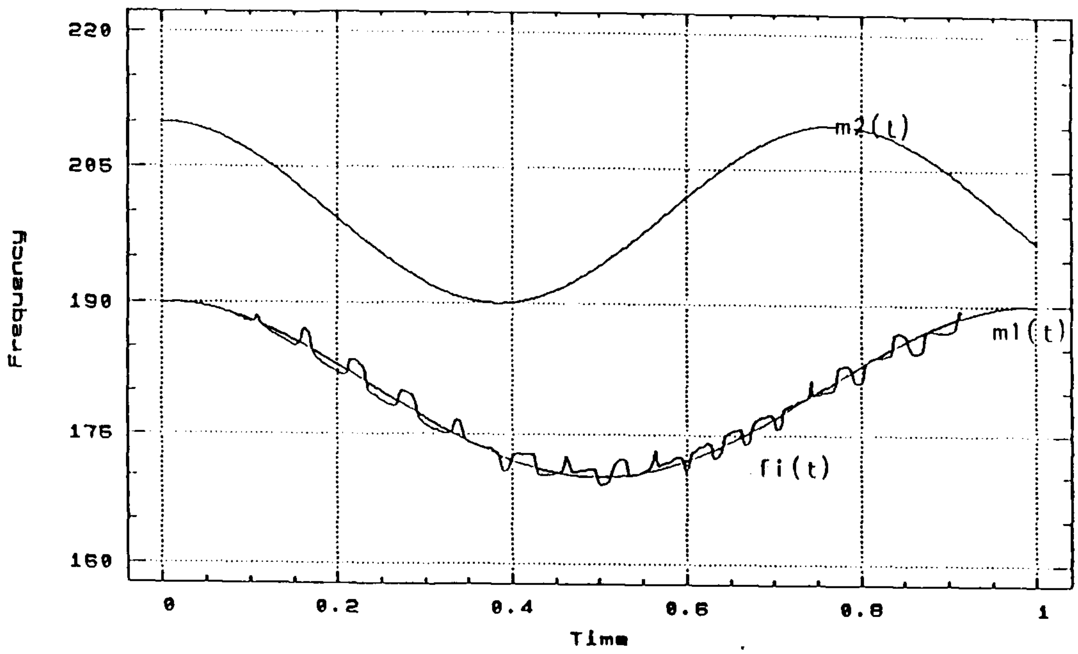


b. $\beta = 10$

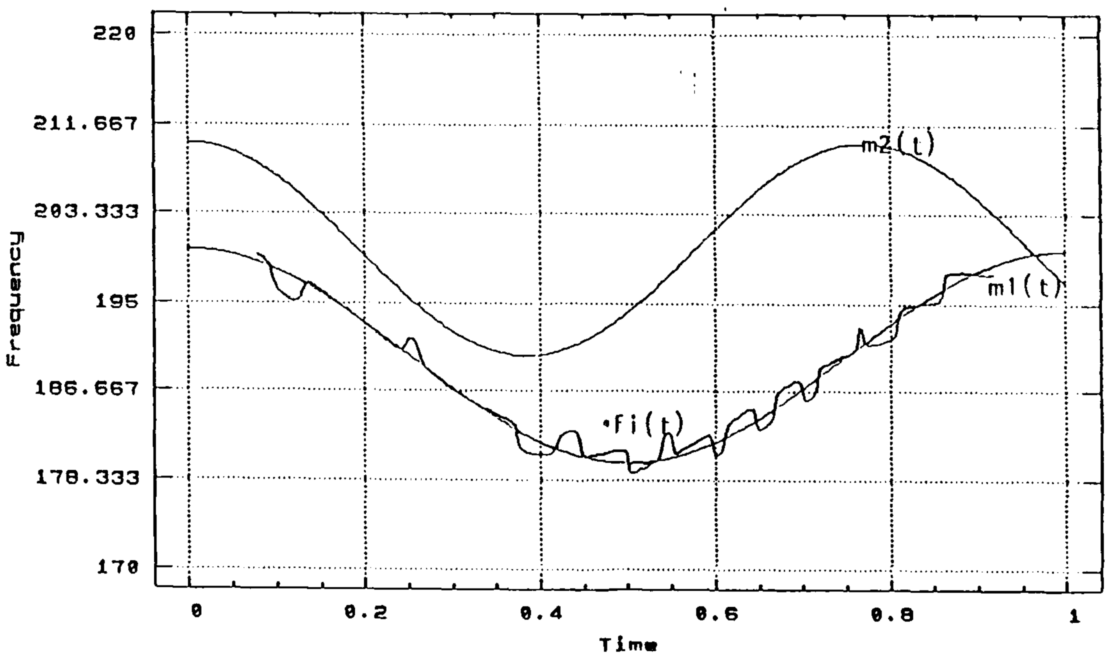


c. $\beta = 50$

Fig. 4.5 Average Instantaneous Frequency Deviation for Tone Messages where $a_1/a_2 = 1.2$, $f_c = 200$ Hz, $f_1 = 1$ Hz, $f_2 = 1.3$ Hz, $N = 60$



a. f_{c1} = 180Hz, f_{c2} = 200Hz



b. f_{c1} = 190Hz, f_{c2} = 200Hz

Fig. 4.6 Average Instantaneous Frequency Deviation for Tone Messages where $a_1/a_2 = 1.2$, $f_1 = 1$ Hz, f_2=1.3 Hz, $\beta = 10$, $N = 60$

V. CONCLUSIONS AND RECOMMENDATIONS

The simulation results establish that the lowpass filtering portion of frequency demodulation accounts for the capture effect of FM receivers. Without filtering, the instantaneous frequency deviation of the sum of two carriers has an impulse–like history which does not consistently favor the message of the dominant carrier. With averaging or smoothing (lowpass filtering) of the instantaneous frequency deviation, capture occurs.

The simulation results indicate capture occurs for both narrowband and wideband FM. Capture is evident when the carriers are separated in amplitude by less than 0.2 dB. The effect of averaging time is revealed by the simulation output. In general, longer averaging times produce smoother approximation to the message of the dominant carrier, as expected, and also show the capture effect more convincingly.

It is recommended that the capture effect be verified using an operating experimental system in which system parameters can be controlled and accurately measured.

APPENDIX

Program List

This appendix contains the program used to calculate $\bar{f}_i$ defined in the thesis. The program actually determines T_i and $\bar{T}_k$ as given by Eq. (3.1).

The input equation is $s_1(t) + s_2(t)$ as defined by Eq.2.6. This equation is sampled 12,000 times in the one second simulation interval. The interval between samples is, then, $1/12{,}000 = 83.3\ \mu\text{sec} = \lambda$. The polarity of each sample value is noted. The number of consecutive sample values of like polarity in interval i is T_i.

The program stores each value of T_i and forms $\bar{T}_k$ from Eq. (3.1) for various assigned values of N. Then $\bar{f}_k$ is calculated according to Eq. (3.2). Finally, $\bar{f}_k$ is plotted for each time index of Eq. (3.4).

The program contents are following:

MAIN	: main routine for the simulation of capture effect
CHIRPGEN	: subfunction routine for generation of CHIRPs
WAVEGEN	: subfunction routine for generation of sinusoidal waves
COUNT	: subfunction routine for counting and averaging
SAMPLE	: subfunction routine for display

The program was written in APL and run on IBM PC/AT with 3 Mb of memory.

A. MAIN

```
    ∇ Y←MAIN A;A;Y;TMPSMP;TSLICE
[1]   ⍝
[2]   ⍝ This is main routine for the capture effect
[3]   ⍝ Simulation. For the clality of logical flow,
[4]   ⍝ each simulation step is divided into their
[5]   ⍝ own routines.
[6]   ⍝ The output will be,
[7]   ⍝  T: time index for f1 and f2
[8]   ⍝  TIME: time index for aceraged frequency
[9]   ⍝        (not equally spaced)
[10]  ⍝  F1,F2: individual instantaneous
[11]  ⍝         frequency
[12]  ⍝  RES: averaged version of frequency
[13]  ⍝
[14]
[15]   ⎕←'Generating waves....'
[16]
[17]  ⍝ Generating arbitrally sinusoidal waves
[18]
[19]   TMPSMP←WAVEGEN A
[20]   ⎕←'Counting....'
[21]
[22]  ⍝ Count the number samples between
[23]  ⍝ zero crossings and form a resulting sequency
[24]
[25]   Y←COUNT TMPSMP
[26]   ⎕←'Sampling....'
[27]
[28]  ⍝ Since the numbers of elements of sampled time and
[29]  ⍝ message are too many for plotting purpose, it is
[30]  ⍝ sampled without missing any important information.
[31]
[32]   T←SAMPLE T
[33]   F1←SAMPLE F1
[34]   F2←SAMPLE F2
[35]   ⎕←'Done.'
    ∇
```

B. CHIRPGEN

```
∇ V←CHIRPGEN A1;⎕IO;A1;A2;PH1;PH2;V;TMP1;TMP
  ⍝ This routine generates two CHIRP signals, namely up
  ⍝ and down CHIRP to test the program.
  ⍝ Equations for this routine are,
  ⍝    F1=100T+150   for up CHIRP
  ⍝    F2=250-100T   for down CHIRP
  ⍝ where 0≤T≤1
   ⎕IO←0
   A2←1
   TSLICE←⌈(1.3*0.5)×10000
   T←(⍳TSLICE)÷TSLICE
   D←50
   TMP←(○2)×D
   TMP←TMP×T
   TMP←TMP×T
   TMP1←(○2)×(200-D)
   TMP1←TMP1×T
   PH1←TMP+TMP1
   TMP←(○2)×(200+D)
   TMP←TMP×T
   TMP1←(○2)×D
   TMP1←TMP1×T
   TMP1←TMP1×T
   PH2←TMP-TMP1
   TMP←2○PH1
   TMP1←2○PH2
   TMP←A1×TMP
   TMP1←A2×TMP1
   V←TMP+TMP1
   V←×V
   F1←2×D×T
   F1←F1+200-D
   F2←200+D
   TMP←2×D
   TMP←TMP×T
   F2←F2-TMP
∇
```

C. WAVEGEN

```
    ∇ V←WAVEGEN A1;⎕IO;A1;A2;V;TMP1;TMP;V1;V2;KF1;KF2
       ;FC1;FC2;FM1;FM2;PH1;PH2;P1;P2
      ⍝
      ⍝ Routine to generate samples of sinusoid waveforms
      ⍝
       ⎕IO←0

      ⍝ Second wave amplitude. This routine accepts the first
      ⍝ signal amplitude as an input argument

       A2←1
       P2←○2
       TSLICE←⌈(1.5*0.5)×10000
       T←(⍳TSLICE)÷TSLICE

      ⍝ Carrier frequency, frequency sensitivity and message
      ⍝ frequency

       FC1←200 ⋄ FC2←200
       KF1←10 ⋄ KF2←10
       FM1←1 ⋄ FM2←1.3
       PH1←0 ⋄ PH2←0
       TMP←P2×FM1
       TMP←TMP×T
       TMP←TMP+PH1
       TMP←1○TMP
       TMP←TMP-(1○PH1)
       TMP←TMP×KF1÷FM1
       TMP1←P2×FC1×T
       TMP←TMP+TMP1
       V1←2○TMP
       V1←V1×A1
       TMP←P2×FM2
       TMP←TMP×T
       TMP←TMP+PH2
       TMP←1○TMP
       TMP←TMP-(1○PH2)
       TMP←TMP×KF2÷FM2
       TMP1←P2×FC2
       TMP1←TMP1×T
       TMP←TMP+TMP1
       V2←2○TMP
       V2←A2×V2
       V←×(V1+V2)
       TMP←P2×FM1
       TMP←TMP×T
       TMP←TMP+PH1
       TMP←KF1×COS(TMP)
       F1←FC1+TMP
       TMP←P2×FM2
       TMP←TMP×T
       TMP←TMP+PH2
       TMP←KF2×COS(TMP)
       F2←FC2+TMP
    ∇
```

D. COUNT

```
    ∇ Y←COUNT V;C;COUNTER;INIT;I;LIMIT;D;Y;TMP
       ;EXTIME1;EXTIME2;INTV

      ⍝Routine to form half period sequence and average it

      ⍝
      ⍝ Set the initial matricies and values
      ⍝
       C←⍬
       COUNTER←0
       INIT←V[⎕IO]
       I←⎕IO
       LIMIT←(⍴V)+⎕IO-1
      ⍝
      ⍝ Routine to count number of samples between
      ⍝ Zero-crossings
      ⍝
      LOOP1:
       →(V[I]=INIT)/LOOP2
       C←C,COUNTER
       INIT←V[I]
       COUNTER←1
       →LOOP3
      LOOP2:
       COUNTER←COUNTER+1
      LOOP3:
       I←I+1
       →(I≤LIMIT)/LOOP1
       C←C,COUNTER
      ⍝
      ⍝ Drop the incomplete cycle at the beginning and the end
      ⍝
       EXTIME1←C[⎕IO]×(1÷TSLICE)
       C←1↓C ⋄ C←¯1↓C
       D←⍬
       TIME←⍬
      ⍝
      ⍝ Average with the value of INTV
      ⍝
       INTV←60
       I←⎕IO
       LIMIT←(⍴C)-(⎕IO+1+INTV)
      ⍝
      ⍝ Calculate extra time due to averaging
      ⍝
       EXTIME2←(+/INTV↑C)÷TSLICE
      ⍝
      ⍝ Calculate the time index which is not equally placed
      ⍝
      LOOP4:
       TMP←+/INTV↑C
       D←D,TMP÷INTV
       TIME←TIME,C[⎕IO]
       C←1↓C
       I←I+1
```

```
[55]  →(I≤LIMIT)/LOOP4
[56]  TIME←((+\TIME)÷TSLICE)+EXTIME1+(EXTIME2÷2)
[57] ⍝
[58] ⍝ Calculate averaged frequency for the time indicies
[59] ⍝
[60]  Y←(1÷2×D)×TSLICE
    ∇
```

E. SAMPLE

```
    ∇ Y←SAMPLE X;⎕IO;Y;SIZ;LIMIT;I;X

     ⍝ Routine to sample for plotting (number of samples = 60

      ⎕IO←0
      Y←⍬
      SIZ←⌊((⍴X)÷600)
      LIMIT←(⍴X)+⎕IO-1
      I←⎕IO
     LABEL1:
      Y←Y,X[I×SIZ]
      I←I+1
      →((I×SIZ)≤LIMIT)/LABEL1
    ∇
```

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3. Haykin, S., *Communication Systems*, John Wiley & Sons, Inc., 1983.

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